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# On the Luminosity of the Ultra High Energy Cosmic Rays Sources

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## Abstract

The energy density of the Ultra High Energy Cosmic Rays (UHECR) in the Universe is a very important parameter for the solution of the puzzle of their origin. It defines the luminosity of the UHECR sources and thus the type of objects they are. This is also of crucial importance for the design of high energy neutrino telescopes. The current attempts to derive the source luminosity are hindered by the small world experimental statistics. We show that the unknown strength and structure of the large scale cosmic magnetic fields affect strongly the UHECR propagation history. The identification of the UHECR sources will bring important information on the large scale magnetic fields.

## 1. Introduction

Ever since the discovery of the microwave background and the conclusions about the end of the UHECR spectrum derived by Greisen (1966) and by Zatsepin and Kuzmin (1966), the first  $10^{20}$  eV air shower detected by John Linsley (1963) was difficult to interpret. We have not progressed that far in 30 years and still argue if the world statistics includes 10 or 20 events. Every giant air shower array has registered at least one super-GZK event and now we hope to have more than one order of magnitude increase by the end of the decade. The rational thing to do is maybe wait until then to make any conclusions. It is not only the intellectual curiosity that makes it very hard to keep silent for such a long time. The extragalactic cosmic rays energy density is a crucial parameter for the expectations from the fast developing high energy neutrino astronomy and for the design of its detectors. On top of this we should be better prepared for the analysis and interpretation of the forthcoming data.

The big disappointment of 2002 was the discrepancy between the results of HiRes (Abu-Zayyad et al.) in monocular mode and those of AGASA (Takeda et al; AGASA web page). One can argue correctly that the statistical significance of the discrepancy is small, although such an assessment requires a conspiracy

between the two groups to bend their maximal systematic errors in opposite directions.

There are two types of differences in the measured UHECR spectrum:

- The normalization of the spectrum between  $10^{18.5}$  and  $10^{19.5}$  eV is of the order of the maximum systematic errors of the two detection techniques and analyses.
- The end of the UHECR spectrum is also different. More exactly, the HiRes data seem to confirm the GZK feature (Bahcall & Waxman) while AGASA's do not.

## 2. The Recent Experimental Data Sets

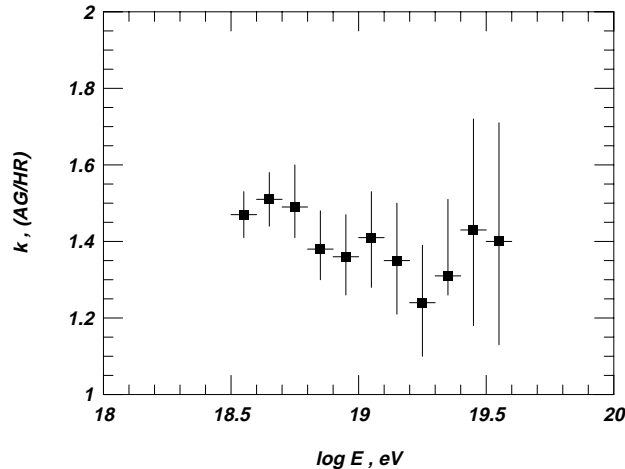
The two experimental groups have obviously very different energy assignments. Since the popular form of the presentation of the spectrum is  $E^3 dN/dE$  the differences are exaggerated in a visual inspection. One can however use the data to define better the difference. If one experiment assigns the wrong energy  $kE$  instead of the correct energy  $E$ ,

$$(kE)^3 \frac{dN}{d(kE)} = k^2 E^3 \frac{dN}{dE} . \quad (1)$$

The same expression can be used to estimate the difference of the energy estimates of the two experiments without the assumption that one of them is wrong. In Fig. 1. we show the  $k$  parameter derived from the comparison of the AGASA and HiRes spectra, which is an indication of the difference in energy assignments as a function of the shower energy.

The ratio of the the energy assignments  $k$  is consistent with a constant values of about 1.4 in the whole energy range. Without any additional knowledge of the reasons for this difference we can draw the conclusion that there are no indications that the HiRes energy assignment is influenced by its energy dependent aperture.

Even if we scale the fluxes respectively up(HiRes) and down(AGASA) by about 20% each and eliminate the difference in the normalization, the inconsistency in the shape of the spectrum remains, although (DeMarco, Blasi & Olinto) it is of a statistical significance lower than  $3\sigma$ . Let me speculate for one of the possible reasons for the disagreement for the rate of the highest energy events. The argument of Bahcall & Waxman is that HiRes has much higher exposure than AGASA but sees one order of magnitude less super-GZK events. Indeed,



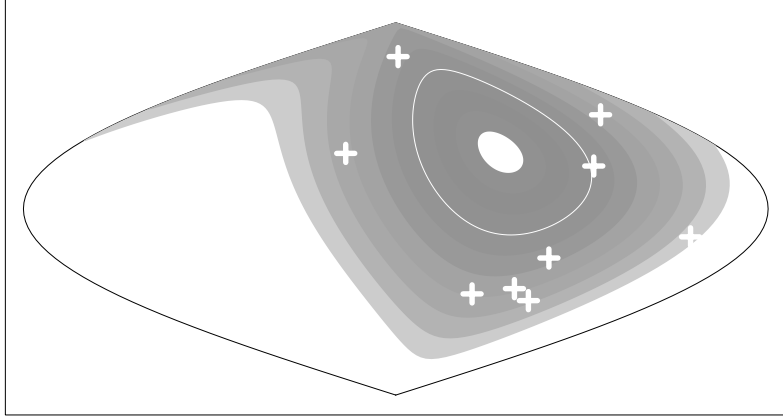
**Fig. 1.**  $k$  factors for the AGASA data based on the HiRes normalization. The error bars are calculated using the high/low flux estimates of the two experiments.

the AGASA experiment gives exposure of  $1,460 \text{ km}^2\text{sr.yrs}$ . The exposure of HiRes is more difficult to estimate, but from the observational time of 0.275 yrs (2410 hrs) of HiRes I and an aperture of  $8,000 \text{ km}^2\text{sr}$  one can estimate the exposure as  $2,200 \text{ km}^2\text{sr.yrs}$ .

### 3. Speculation: Different Fields of View

There is, however, a big difference in the sky areas that are observed by the two experiments. AGASA is restricted to zenith angle of  $45^\circ$ , while the maximum efficiency for the HiRes is at higher zenith angles and sensitivity extends up to  $80^\circ$ . Using a published MonteCarlo zenith angle distribution for HiRes (which is in a good agreement with data) and assuming a flat zenith angle efficiency for AGASA, I estimated viewing efficiency of the two experiments for different regions of the sky. The estimate for AGASA is certainly not grossly wrong because of its long observation time. The HiRes has only run for a short time and has not made its RA distribution uniform, as I have assumed. HiRes' field of view that I estimated should be taken with a grain of salt.

Fig. 2. shows the exposure of AGASA and the arrival directions of the super-GZK events. The exposure is calculated in declination bands (assuming uniform RA distribution) and then plotted in Galactic coordinates. One can outline the region of the sky that yields the AGASA events - the white line in Fig. 2.. AGASA has exposure of  $900 \text{ km}^2\text{sr.yrs}$  for this region. HiRes I has a similar exposure of  $850 \text{ km}^2\text{sr.yrs}$ . It is certainly premature to claim that 100



**Fig. 2.** The exposure of AGASA and the arrival directions of the showers of energy exceeding 100 EeV. The shading is proportional to the exposure to different areas in the sky.

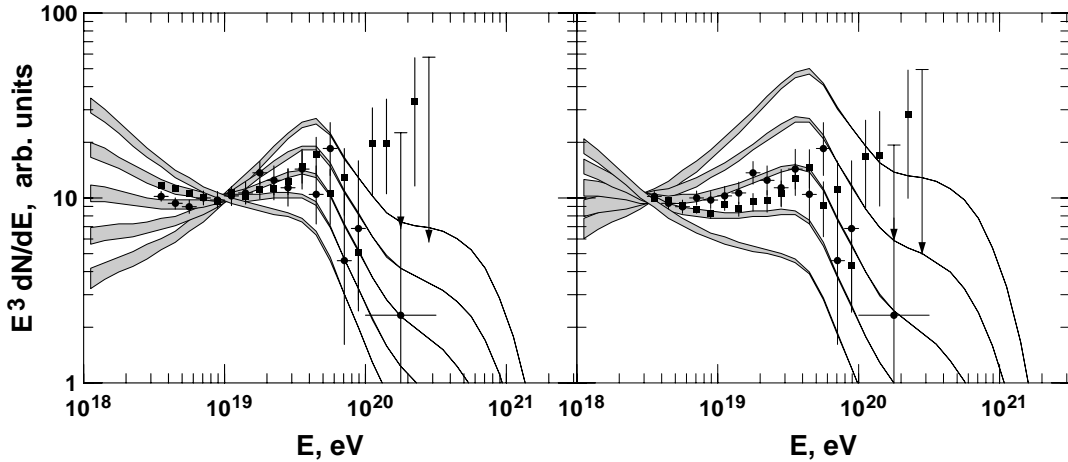
EeV and above events come from certain region of the sky. On the other hand, we are searching for the location of their sources, and should take into account the different fields of view of the experiments.

#### 4. Source Luminosity Estimates

Returning to the source luminosity estimates, the 40% difference in the energy assignment is one of the smallest errors in the determination of the UHECR energy density. A much bigger factor is the position at which a researcher chooses to normalize to the UHECR flux and the assumed injection spectrum that is used to fit the data. Even for a flat astrophysical bottom-up scenario, a downward shift of the normalization point by half an order of magnitude increases the luminosity estimate by an order of magnitude in the  $E^{-3}$  part of the spectrum. If steeper injection spectra are considered as a better fit to the observed spectrum, the difference could reach orders of magnitude. The most important reason is that the total source luminosity should account for the acceleration of all lower energy particles that may be hidden behind the Galactic cosmic ray spectrum. The lowest possible luminosity is predicted for super relativistic shocks, where the accelerated particle has a minimum energy  $m_p \gamma_{shock}^2$  (Achterberg et al. 2001), i.e. about  $10^{15}$  eV for  $\gamma_{shock}$  of 1000. In the case of non relativistic shocks, where the spectrum extends all the way down to the proton mass, the luminosity requirements are higher.

Fig. 3. gives examples of fitting the UHECR spectrum with different injection spectra of isotropic homogeneous source distribution neglecting the existence

of cosmic magnetic fields.



**Fig. 3.** The data of AGASA (squares) and HiRes (dots) are compared to the predictions for the flux arriving at Earth by an isotropic source distribution. See text for details. Right hand panel - normalization at  $10^{18.5}$  eV. Left hand panel - normalization at  $10^{19}$  eV.

The curves in Fig. 3. are for power law injection spectra with indices of 2.00, 2.25, 2.50, 2.75 and 3.00 and an exponential cutoff at  $10^{21.5}$  eV. The expectations are calculated for two different cosmological evolutions of the sources of the form  $(1+z)^n$  with  $n = 3, 4$  (lower and upper edge of shaded spectra) to a maximum at  $z_{max} = 1.8$ . The value of  $z_{max}$  is irrelevant because redshifts larger than 0.5 do not contribute to the fluxes above  $10^{18}$  eV for a maximum injection energy of  $10^{21.5}$  eV.

At least two recent analyses have discussed the data sets in terms of the end of the cosmic ray spectrum. Bahcall & Waxman dismiss the AGASA data and reach the conclusion that the GZK cutoff exists and is best described by a differential power law injection spectrum with  $\alpha = 2$ . For injection energies  $10^{15}$  to  $10^{21}$  eV this model requires cosmic ray luminosity of  $1.4 \times 10^{45}$  erg.Mpc $^{-3}$ yr $^{-1}$ .

The visual inspection of the left hand panel of Fig. 3. does not suggest that any of the data sets in question can be fitted with  $E^{-2}$  injection spectrum. HiRes data seem more consistent with injection spectral index of about 2.5. The same is true for the AGASA data up to  $10^{20}$  eV. It is worth remembering that detailed studies of relativistic shock acceleration predicts spectral indices of 2.2 - 2.3 (Achterberg et al. 2001).

The other analysis (Berezinsky, Gazizov & Grigorieva), which neglects the HiRes results, derives an injection spectrum with  $\alpha = 2.7$ , that is accompanied

by top-down origin of the AGASA super-GZK events. We have to agree with this conclusion at least in the range  $10^{18.5} - 10^{19.5}$  eV, where the  $\alpha = 2.75$  injection predicts best the shape of the experimental data. The total luminosity required under the same conditions is  $4.5 \times 10^{47}$  erg.Mpc $^{-3}$ yr $^{-1}$ . I will use these two numbers to bracket the uncertainty in the UHECR luminosity, which is then a factor of 300.

## 5. Cosmic Magnetic Fields

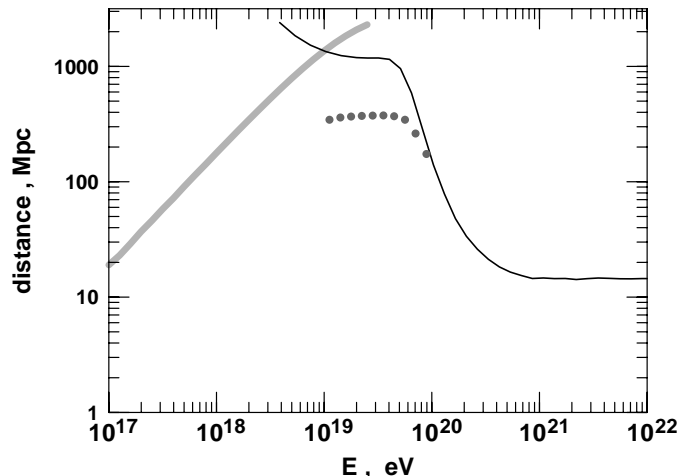
Fig. 3. demonstrates one potential problem with steep injection spectra - such models overproduce at energies around  $10^{18}$  eV. This excess can be easily accommodated if we account for the cosmic magnetic fields. Achterberg et al (1999) derive the scattering angles of UHECR protons in random magnetic fields and related increase of pathlength and time delay. Assuming small angle scattering, the expression for the time delay  $\Delta t$  is

$$\Delta t = 30 \left( \frac{(D/\text{Mpc})^2 (B/\text{nG})^2}{E_{20}^2} \right) (l_0/\text{Mpc}) \text{ yrs} , \quad (2)$$

where  $E_{20}$  is the proton energy in units of  $10^{20}$  eV and  $l_0$  is the coherence length of the random field. This expression does not account for the proton energy loss and is the *minimum*  $\Delta t$ . The time delay  $\Delta t$  is the excess travel time over the straight line propagation time  $t$ . The total propagation time  $t + \Delta t$  has to be less than Hubble time. This requirement restricts the distance from the source to the observer. As an illustration I show on Fig. 4. what are the limits on that distance for Hubble time of  $10^{10}$  yrs and field strength of 1 nG.

Stanev et al. (2000) estimated the proton energy loss in the presence of random magnetic field. The technique applied was Monte Carlo and simulations to Hubble time are very inefficient. Fig. 4. shows the maximum distance allowed by the Hubble time constraint with no energy loss (thick gray line) in 1 nG field and the energy loss alone (solid line). The points show a part of the transitional region, as calculated for the horizon  $R_{50}$  by Stanev et al. (2000). Because of energy loss the time constraint would be much stronger if the Universe indeed contain 1 nG random magnetic field and if the cosmic ray sources are isotropically and uniformly distributed. The time delay restriction would eliminate any excess cosmic ray events in the case of a relatively steep injection spectrum.

The possible existence of regular large scale fields complicates the derivation of the injection spectrum even more. The following exercise by Stanev, Seckel & Engel (2001) demonstrates the problems: a cosmic ray source at the origin injects isotropically protons above  $10^{18.5}$  eV on a power law spectrum with exponential cutoff at  $10^{21.5}$  eV. The source is in the central  $yz$  plane of a 3 Mpc



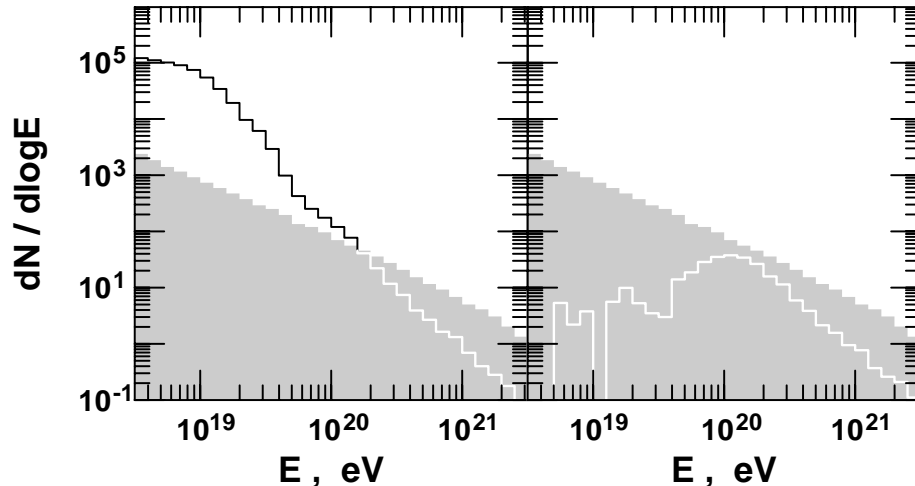
**Fig. 4.** Restrictions on the distance from which UHECR can reach us. The solid line show the proton energy loss distance. The thick gray line show the time delay restriction. The points are for the horizon calculated by Stanev et al. (2000).

wide magnetic wall, that is a simplified version of the Supergalactic plane (SGP). Magnetic field with strength of  $B_{reg} = 10$  nG points in  $z$  direction and decays exponentially outside the SGP. The regular field is accompanied by random field with strength  $B_{randm} = B_{reg}/2$ .

Protons are followed with energy loss until they intersect a sphere of radius 20 Mpc. Their exit positions, velocity vectors and energies are recorded. The correlation between these parameters are studied in the analysis of the simulation. Fig. 5. shows the energy spectrum of the protons leaving the sphere at two  $9 \text{ Mpc}^2$  patches: the *front* patch around  $z = 20$  Mpc inside the SGP, and the *side* patch with the same area around  $x = 20$  Mpc, i.e. in direction perpendicular to the magnetic field.

The locations of the two patches in Fig. 5. are chosen because the exit proton spectra are very different at these positions. Protons of energy below  $10^{20}$  eV are often caught in the SGP magnetic field and can not leave it. They gyrate back and forth around the magnetic field lines and are equally likely to leave the 20 Mpc sphere through the *front* and the symmetric *back* patches. Because of these particles that are trapped in the magnetic wall the exit spectra at  $10^{19}$  eV in these patches are higher than the injection spectra by 2 orders of magnitude. At higher energies the protons propagate almost rectilinearly. The decrease in the spectrum is due to energy loss.

Protons exiting through the *side* patch show exactly the opposite picture. To reach the patch the protons have to cross the magnetic field lines and very



**Fig. 5.** Energy distribution of the protons leaving the *front* patch (left) and the *side* patch (right) at 20 Mpc from an isotropic cosmic ray source. See the text for a description of the geometry. The shaded histogram shows the energy spectra of the protons emitted in the direction of the patches.

few lower energy particles can do that with the help of the random field. In the vicinity of  $10^{19}$  eV the exit spectrum is more than two orders of magnitude short of the injection spectrum. Above  $2 \times 10^{20}$  eV the two exit spectra are identical.

If two observers were estimating the proton injection spectra with no account for the magnetic fields at  $10^{19}$  eV, their estimates would differ by four orders of magnitude. Similar, although not as strong, effects are also visible in these patches for UHE cosmic ray sources outside the 20 Mpc sphere that illuminate the SGP.

In these simple cases one can scale the effects in proton energy as a function of the magnetic field strength. If  $B_{reg}$  were 5 nG, all effects would be the same but at energies that are twice as high. Large scale fields of strength 10 nG extending through a small fraction of the volume of the Universe are not an extreme assumption. The effects demonstrated in Fig. 5. will certainly happen at certain level in the real Universe.

## 6. Conclusions

- The energy assignments of the AGASA and HiRes experiments are different by about 40%. This difference appears to be constant between  $10^{18.5}$  and  $10^{19.5}$  eV. The data of the Auger Observatory in hybrid mode should help resolve this difference. The different fields of view of the two experi-



ments might also have some relevance to the detected number of super-GZK events.

- Correct estimates of the UHECR source luminosity are at present not possible because of the very limited statistics. All experiments have seen super-GZK events but the shape of the spectrum is not well determined.
- Even in the future, when we hope to increase the available statistics by orders of magnitude, this will not be an easy task. The main problem is not how high in energy the UHECR spectrum continues, but how low is the energy that we have to include in the total source luminosity. The solution should come from the acceleration models.
- This becomes a serious uncertainty if the cosmic ray acceleration spectrum is fit with power law spectra steeper than  $E^{-2}$ . The injection spectrum that fits best the current statistics is not flatter than  $E^{-2.5}$ .
- The possible existence of random extragalactic fields restrict the distance that protons of fixed energy can reach in Hubble time to our local cosmological neighborhood. Extragalactic protons below  $10^{17}$  eV are restricted to a few Mpc and those above  $10^{20.5}$  to about 15 Mpc.
- The possible existence of regular fields of extension of  $\sim 40$  Mpc and strength of order 10 nG affects strongly the propagation of  $10^{18}$  -  $10^{20}$  eV protons. The ‘arrival’ spectra in this energy range depend on the relative positions of the source and the observer with respect to the magnetic field direction and structure.
- Only protons of energy well above  $10^{20}$  eV reveal the source spectrum after an account for the energy loss on propagation. Hopefully the Auger Observatory, and later EUSO and OWL, will collect significant statistics of such events that will reveal the type and the luminosity of the UHECR sources.

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